

DO STRANGE STARS EXIST IN THE UNIVERSE?

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Abstract. Definitely, an affirmative answer to this question would have implications of fundamental importance for astrophysics (a new class of compact stars), and for the physics of strong interactions (deconfined phase of quark matter, and strange matter hypothesis). In the present work, we use observational data for the newly discovered millisecond X-ray pulsar SAX J1808.4-3658 and for the atoll source 4U 1728-34 to constrain the radius of the underlying compact stars. Comparing the mass-radius relation of these two compact stars with theoretical models for both neutron stars and strange stars, we argue that a strange star model is more consistent with SAX J1808.4-3658 and 4U 1728-34, and suggest that they are likely strange star candidates.

1. Introduction

The possible existence of a new class of compact stars, which are made entirely of deconfined u, d, s quark matter (*strange quark matter* (SQM)), is one of the most intriguing aspects of modern astrophysics. These compact objects are called strange stars. They differ from neutron stars, where quarks are confined within neutrons, protons, and eventually within other hadrons (*e.g. hyperons*). The investigation of such a possibility is relevant not only for astrophysics, but for high energy physics too. In fact, the search for a deconfined phase of quark matter is one of the main goals in heavy ion physics. Experiments at Brookhaven National Lab's Relativistic Heavy Ion Collider (RHIC) and at CERN's Large Hadron Collider (LHC), will hopefully clarify this issue in the near future.

The possibility that strange stars do exist is based on the so called *strange matter hypothesis*, formulated by Witten (1984) (see also Bodmer, 1971). According to this hypothesis, strange quark matter, in equilibrium with respect to the weak interactions, could be the true ground state of strongly interacting matter rather than ^{56}Fe , *i.e.* the energy per baryon of SQM must fulfil the inequality

$$\left(\frac{E}{A}\right)_{\text{SQM}} \leq \frac{E(^{56}\text{Fe})}{56} \simeq 930 \text{ MeV}, \quad (1)$$

at the baryon density where the pressure is equal to zero.

If the strange matter hypothesis is true, then a nucleus with A nucleons, could in principle lower its energy by converting to a strangelet (a drop of SQM). However, this process requires a very high-order simultaneous weak interactions

to convert about a number A of u and d quarks of the nucleus into strange quarks. The probability for such a process is extremely low ¹, and the mean life time for an atomic nucleus to decay to a strangelet is much higher than the age of the Universe. On the other hand, a step by step production of s quarks, at different times, will produce hyperons in the nucleus, *i.e.* a system (hypernucleus) with a higher energy per baryon with respect to the original nucleus. In addition, finite size effects (surface and shell effects) place a lower limit ($A \sim 10\text{--}100$) on the baryon number of a stable strangelet even if bulk SQM is stable (Farhi & Jaffe, 1984). Thus, according to the strange matter hypothesis, the ordinary state of matter, in which quarks are confined within hadrons, is a metastable state.

The success of traditional nuclear physics, in explaining an astonishing amount of experimental data, provides a clear indication that quarks in a nucleus are confined within protons and neutrons. Thus, the energy per baryon $(E/A)_{ud}$ of u, d quark matter (nonstrange quark matter) must be higher than the energy per baryon of nuclei

$$\left(\frac{E}{A}\right)_{ud} \geq 930 \text{ MeV} + \Delta, \quad (2)$$

being $\Delta \sim 4 \text{ MeV}$ a quantity which accounts for the lower energy per baryon of a finite chunk ($A \sim 250$) of nonstrange quark matter with respect to the bulk ($A \rightarrow \infty$) case (Farhi & Jaffe, 1984). These stability conditions (eq.s (1) and (2)) in turn may be used to constrain the parameters entering in models for the equation of state (EOS) of SQM. As we show below, the existence of strange stars is allowable within the uncertainties inherent in perturbative Quantum Chromo-Dynamics (QCD). Thus *strange stars may exist in the Universe*.

2. The equation of state for strange quark matter

From a basic point of view the equation of state for SQM should be calculated solving the equations of QCD. As we know, such a fundamental approach is presently not doable. Therefore one has to rely on phenomenological models. In this work, we discuss two phenomenological models for the EOS of strange quark matter. The first one is a well known model related to the MIT bag model (Chodos *et al.* 1974) for hadrons. The second one is a new model developed by Dey *et al.* (1998).

At very high density SQM behaves as a relativistic gas of weakly interacting fermions. This is a consequence of one of the basic features of QCD, namely asymptotic freedom. To begin with consider the case of massless quarks, and consider gluon exchange interactions to the first order in the QCD structure constant α_c . Under these circumstances the EOS of β -stable SQM can be written in the parametrical form:

$$\varepsilon = K n_B^{4/3} + B, \quad P = \frac{1}{3} K n_B^{4/3} - B, \quad K \equiv \frac{9}{4} \pi^{2/3} \left(1 + \frac{2\alpha_c}{3\pi}\right) \hbar c \quad (3)$$

¹ It is proportional to $G_F^2 A$, being G_F the Fermi constant, and assuming a number A of simultaneous weak processes.

ε being the energy density, and P the pressure. Eliminating the baryon number density n_B one gets:

$$P = \frac{1}{3}(\varepsilon - 4B) \quad (4)$$

Here B is a phenomenological parameter which represents the difference between the energy density of “perturbative vacuum” and true QCD vacuum. B is related to the “bag constant” which in the MIT bag model for hadrons (Chodos *et al.* 1974) gives the confinement of quarks within the hadronic bag. The density of zero pressure SQM is just $\rho_s = 4B/c^2$. This is the value of the surface density of a bare strange star. Taking a non-vanishing value for the mass m_s of the strange quark, the EOS becomes more involved (see *e.g.* Farhi & Jaffe, 1984) with respect to the simple expression (4). However, for $m_s = 100$ – 300 MeV, equation (4) is less than 5% different from the “exact” case for $m_s \neq 0$. In summary, in this model for the equation of state for SQM there are three phenomenological parameters, namely: B , m_s , and α_c . It is possible to determine ranges in the values of these parameters in which SQM is stable, and nonstrange quark matter is not (Farhi & Jaffe, 1984). For example, in the case of non-interacting quarks ($\alpha_c = 0$) one has $B \simeq 57$ – 91 MeV/fm³ for $m_s = 0$, and $B \simeq 57$ – 75 MeV/fm³ for $m_s = 150$ MeV.

The schematic model outlined above becomes less and less trustworthy going from very high density region (asymptotic freedom regime) to lower densities, where confinement (hadrons formation) takes place. Recently, Dey *et al.* (1998) derived a new EOS for SQM using a “dynamical” density-dependent approach to confinement. The EOS by Dey *et al.* has asymptotic freedom built in, shows confinement at zero baryon density, deconfinement at high density. In this model, the quark interaction is described by a colour-Debye-screened inter-quark vector potential originating from gluon exchange, and by a density-dependent scalar potential which restores chiral symmetry at high density (in the limit of massless quarks). The density-dependent scalar potential arises from the density dependence of the in-medium effective quark masses M_q , which, in the model by Dey *et al.* (1998), are taken to depend upon the baryon number density according to

$$M_q = m_q + 310 \cdot \text{sech}\left(\nu \frac{n_B}{n_0}\right) \quad (\text{MeV}), \quad (5)$$

where $n_0 = 0.16$ fm⁻³ is the normal nuclear matter density, $q(= u, d, s)$ is the flavor index, and ν is a parameter. The effective quark mass $M_q(n_B)$ goes from its constituent masses at zero density, to its current mass m_q , as n_B goes to infinity. Here we consider two different parameterizations of the EOS by Dey *et al.*, which correspond to a different choice for the parameter ν . The equation of state SS1 (SS2) corresponds to $\nu = 0.333$ ($\nu = 0.286$). These two models for the EOS give absolutely stable SQM according to the strange matter hypothesis.

3. Strange star candidates

To distinguish whether a compact star is a neutron star or a strange star, one has to find a clear observational signature. There is a striking qualitative difference in the mass-radius (MR) relation of strange stars with respect to that

of neutron stars (see Fig. 1). For strange stars with “small” ($M \ll M_{max}$) gravitational mass, M is proportional to R^3 . In contrast, neutron stars have radii that decrease with increasing mass. This is a consequence of the underlying interaction between the stellar constituents which makes “low” mass strange stars self-bound objects (see *e.g.* Bombaci 1999) contrary to the case of neutron stars which are bound by gravity². As we know, there is a minimum mass for a neutron star ($M_{min} \sim 0.1 M_{\odot}$). In the case of a strange star, there is essentially no minimum mass. As the central density $\rho_c \rightarrow \rho_s$ (surface density), a strange star (or better a strangelet for very low baryon number) is a self-bound system, until the baryon number becomes so low that finite size effects destabilize it.

3.1. SAX J1808.4-3658

The transient X-ray burst source SAX J1808.4-3658 was discovered in September 1996 by the BeppoSAX satellite. Two bright type-I X-ray bursts were detected, each lasting less than 30 seconds. Analysis of the bursts in SAX J1808.4-3658 indicates that it is 4 kpc distant and has a peak X-ray luminosity of 6×10^{36} erg/s in its bright state, and a X-ray luminosity lower than 10^{35} erg/s in quiescence (in’t Zand 1998). The object is nearly certainly the same as the transient X-ray source detected with the Proportional Counter Array (PCA) on board the Rossi X-ray Timing Explorer (RXTE) (Marshall, 1998). Coherent pulsations at a period of 2.49 milliseconds were discovered (Wijnands & van der Klis 1998). The star’s surface dipolar magnetic moment was derived to be less than 10^{26} G cm³ from detection of X-ray pulsations at a luminosity of 10^{36} erg/s (Wijnands & van der Klis 1998), consistent with the weak fields expected for type-I X-ray bursters and millisecond radio pulsars (MS PSRs) (Bhattacharya & van den Heuvel 1991). The binary nature of SAX J1808.4-3658 was firmly established with the detection of a 2 hour orbital period (Chakrabarty & Morgan 1998) as well as with the optical identification of the companion star (Roche *et al.* 1998). SAX J1808.4-3658 is the first pulsar to show both coherent pulsations in its persistent emission and X-ray bursts, and by far the fastest-rotating, lowest-field accretion-driven pulsar known. It presents direct evidence for the evolutionary link between low-mass X-ray binaries (LMXBs) and MS PSRs. SAX J1808.4-3658 is the only known LMXB with an MS PSR.

A mass-radius (MR) relation for the compact star in SAX J1808.4-3658 has been recently obtained by Li *et al.* (1999a)³ using the following two requirements. (i) Detection of X-ray pulsations requires that the inner radius R_0 of the accretion flow should be larger than the stellar radius R . In other words, the stellar magnetic field must be strong enough to disrupt the disk flow above the stellar surface. (ii) The radius R_0 must be less than the so-called co-rotation radius R_c , *i.e.* the stellar magnetic field must be weak enough that accretion is not centrifugally inhibited:

$$R_0 \lesssim R_c = [GMP^2/(4\pi^2)]^{1/3}. \quad (6)$$

² As an idealized example, remember that pure neutron matter is not bound by nuclear forces.

³ see also Burderi & King (1998), Psaltis & Chakrabarty (1999).

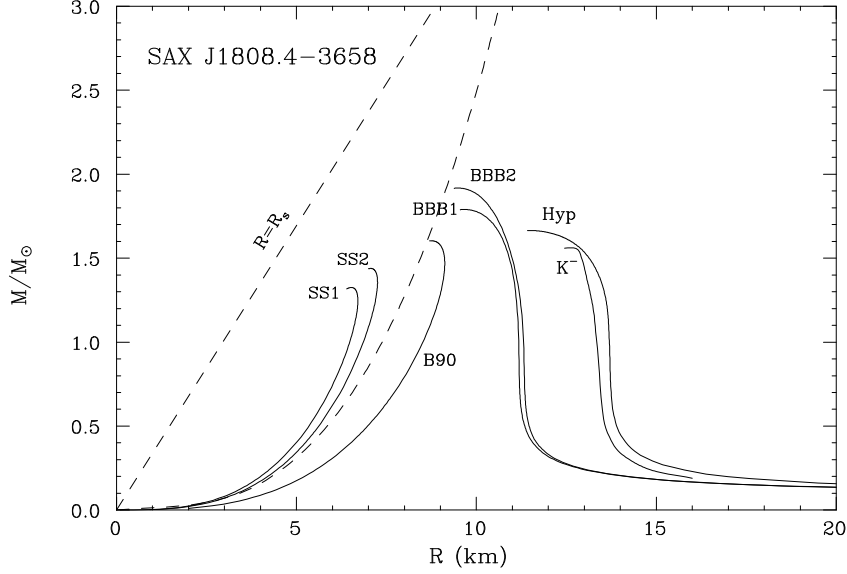


Figure 1. Comparison of the mass–radius relation of SAX J1808.4–3658 determined from RXTE observations with theoretical models of neutron stars and of strange stars. See text for more details.

Here G is the gravitation constant, M is the mass of the star, and P is the pulse period. The inner disk radius R_0 is generally evaluated in terms of the Alfvén radius R_A , at which the magnetic and material stresses balance (Bhattacharya & van den Heuvel 1991): $R_0 = \xi R_A = \xi [B^2 R^6 / \dot{M} (2GM)^{1/2}]^{2/7}$, where B and \dot{M} are respectively the surface magnetic field and the mass accretion rate of the pulsar, and ξ is a parameter of order of unity almost independent of \dot{M} (Li 1997, Burderi & King 1998). Since X-ray pulsations in SAX J1808.4-3658 were detected over a wide range of mass accretion rate (say, from \dot{M}_{\min} to \dot{M}_{\max}), the two conditions (i) and (ii) give $R \lesssim R_0(\dot{M}_{\max}) < R_0(\dot{M}_{\min}) \lesssim R_c$. Next, we assume that the mass accretion rate \dot{M} is proportional to the X-ray flux F observed with RXTE. This is guaranteed by the fact that the X-ray spectrum of SAX J1808.4-3658 was remarkably stable and there was only slight increase in the pulse amplitude when the X-ray luminosity varied by a factor of ~ 100 during the 1998 April/May outburst (Gilfanov *et al.* 1998, Cui *et al.* 1998, Psaltis & Chakrabarty 1999). Therefore, Li *et al.* (1999a) get the following upper limit of the stellar radius: $R < (F_{\min}/F_{\max})^{2/7} R_c$, or

$$R < 27.5 \left(\frac{F_{\min}}{F_{\max}} \right)^{2/7} \left(\frac{P}{2.49 \text{ ms}} \right)^{2/3} \left(\frac{M}{M_{\odot}} \right)^{1/3} \text{ km}, \quad (7)$$

where F_{\max} and F_{\min} denote the X-ray fluxes measured during X-ray high- and low-state, respectively, M_{\odot} is the solar mass. Note that in writing inequality (7)

it is assumed that the pulsar's magnetic field is basically dipolar (see Li *et al.* 1999a for arguments to support this hypothesis)⁴.

Given the range of X-ray flux at which coherent pulsations were detected, inequality (7) defines a limiting curve in the mass-radius plane for SAX J1808.4-3658, as plotted in the dashed curve in Fig. 1. The authors of ref. (Li *et al.* 1999a) adopted the flux ratio $F_{\max}/F_{\min} \simeq 100$ from the observations that during the 1998 April/May outburst, the maximum 2–30 keV flux of SAX J1808.4-3658 at the peak of the outburst was $F_{\max} \simeq 3 \times 10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1}$, while the pulse signal became barely detectable when the flux dropped below $F_{\min} \simeq 2 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$ (Cui *et al.* 1998, Psaltis & Chakrabarty 1999). The dashed line $R = R_s \equiv 2GM/c^2$ represents the Schwarzschild radius - the lower limit of the stellar radius to prevent the star collapsing into a black hole. Thus the allowed range of the mass and radius of SAX J1808.4-3658 is the region confined by these two dashed curves in Fig. 1.

In the same figure, we report the theoretical MR relations (solid curves) for neutron stars given by some recent realistic models for the EOS of dense matter (see Li *et al.* 1999a for references to the EOS models). Models BBB1 and BBB2 are relative to “conventional” neutron stars (*i.e.* the core of the star is assumed to be composed by an uncharged mixture of neutrons, protons, electrons and muons in equilibrium with respect to the weak interaction). The curve labeled Hyp depicts the MR relation for a neutron star in which hyperons are considered in addition to nucleons as hadronic constituents. The MR curve labeled K^- is relative to neutron stars with a Bose-Einstein condensate of negative kaons in their cores. It is clearly seen in Fig. 1 that none of the neutron star MR curves is consistent with SAX J1808.4-3658. Including rotational effects will shift the MR curves to up-right in Fig. 1 (Datta *et al.* 1998), and does not help improve the consistency between the theoretical neutron star models and observations of SAX J1808.4-3658. Therefore SAX J1808.4-3658 is not well described by a neutron star model. The curve B90 in Fig. 1 gives the MR relation for strange stars described by the schematic EOS (4) with $B = 90 \text{ MeV/fm}^3$. The two curves SS1 and SS2 give the MR relation for strange stars calculated with the EOS by Dey *et al.* (1998). Figure 1 clearly demonstrates that a strange star model is more compatible with SAX J1808.4-3658 than a neutron star one.

3.2. 4U 1728-34

Recently, Li *et al.* (1999b) investigated possible signatures for the existence of strange stars in connection with the newly discovered phenomenon of kilohertz quasi-periodic oscillations (kHz QPOs) in the X-ray flux from LMXB (for a review see van der Klis 2000). Initially, kHz QPO data from various sources were interpreted assuming a simple *beat-frequency model* (see *e.g.* Kaaret & Ford 1997). In many cases, two simultaneous kHz QPO peaks (“twin peaks”) are observed. The QPO frequencies vary and are strongly correlated with source flux. In the beat-frequency model the highest observed QPO frequency ν_u is interpreted as the Keplerian orbital frequency ν_K at the inner edge of the accretion

⁴ see also Psaltis & Chakrabarty (1999) for a study of the influence on the MR relation for SAX J1808.4-3658 of a quadrupole magnetic moment, and of a *non-standard* disk-magnetosphere interaction model.

disk. The frequency ν_l of the lower QPO peak is instead interpreted as the beat frequency between ν_K and the neutron star spin frequency ν_0 , which within this model is equal to the separation frequency $\Delta\nu \equiv \nu_u - \nu_l$ of the two peaks. Thus $\Delta\nu$ is predicted to be constant. Nevertheless, novel observations for different kHz QPO sources have challenged this simple beat-frequency model. The most striking case is the source 4U 1728-34, where it was found that $\Delta\nu$ decreases significantly, from 349.3 ± 1.7 Hz to 278.7 ± 11.6 Hz, as the frequency of the lower kHz QPO increases (Méndez & van der Klis 1999). Furthermore, in the spectra observed by the RXTE for 4U 1728-34, Ford & van der Klis (1998) found low-frequency Lorentian oscillations with frequencies between 10 and 50 Hz. These frequencies as well as the break frequency (ν_{break}) of the power spectrum density for the same source were shown to be correlated with ν_u and ν_l .

A different model was recently developed by Osherovich & Titarchuk (1999) (see also Titarchuk & Osherovich 1999), who proposed a unified classification of kHz QPOs and the related observed low frequency phenomena. In this model, kHz QPOs are modeled as Keplerian oscillations under the influence of the Coriolis force in a rotating frame of reference (magnetosphere). The frequency ν_l of the lower kHz QPO peak is the Keplerian frequency at the outer edge of a viscous transition layer between the Keplerian disk and the surface of the compact star. The frequency ν_u is a hybrid frequency related to the rotational frequency ν_m of the star's magnetosphere by: $\nu_u^2 = \nu_K^2 + (2\nu_m)^2$. The observed low Lorentzian frequency in 4U 1728-34 is suggested to be associated with radial oscillations in the viscous transition layer of the disk, whereas the observed break frequency is determined by the characteristic diffusion time of the inward motion of the matter in the accretion flow (Titarchuk & Osherovich 1999). Predictions of this model regarding relations between the QPO frequencies mentioned above compare favorably with recent observations for 4U 1728-34, Sco X-1, 4U 1608-52, and 4U 1702-429.

The presence of the break frequency and the correlated Lorentzian frequency suggests the introduction of a new scale in the phenomenon. One attractive feature of the model by Titarchuk & Osherovich (1999) is the introduction of such a scale in the model through the Reynolds number for the accretion flow. The best fit for the observed data was obtained by Titarchuk & Osherovich (1999) when

$$a_k = (M/M_\odot)(R_0/3R_s)^{3/2}(\nu_0/364 \text{ Hz}) = 1.03, \quad (8)$$

where M is the stellar mass, R_0 is the inner edge of the accretion disk ⁵, R_s is the Schwarzschild radius, and ν_0 is the spin frequency of the star. Given the 364 Hz spin frequency of 4U 1728-34 (Strohmayer et al. 1996), the inner disk radius can be derived from the previous equation. Since the innermost radius of the disk must be larger than the radius R of the star itself, this leads to a mass-dependent upper bound on the stellar radius,

$$R \leq R_0 \simeq 8.86 a_k^{2/3} (M/M_\odot)^{1/3} \text{ km}, \quad (9)$$

⁵ In the expression for a_k reported in Titarchuk & Osherovich (1999), one has $x_0 = R_0/R_s$, where R_0 is erroneously indicated as the neutron star radius (Titarchuk, private communication).

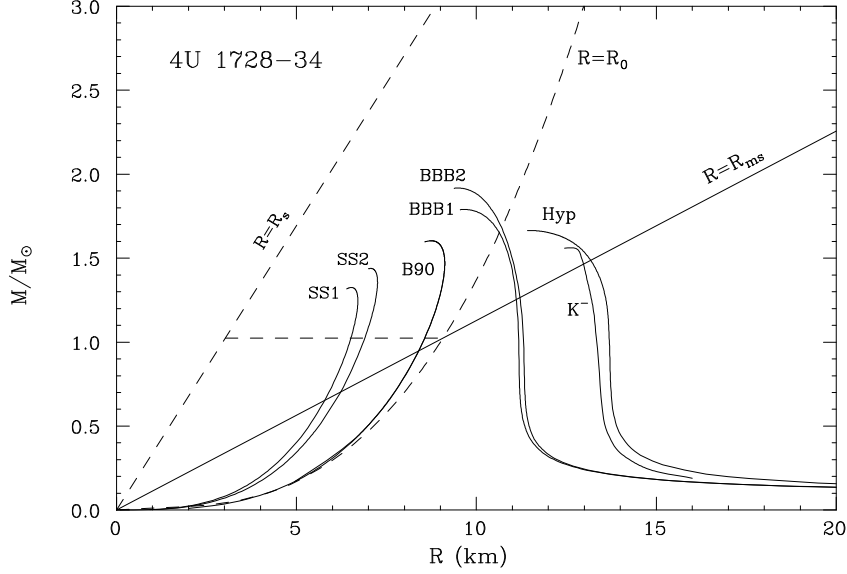


Figure 2. Comparison of the MR relation of 4U 1728-34 determined from RXTE observations with theoretical models of neutron stars and of strange stars. The range of mass and radius of 4U 1728-34 is allowed in the region outlined by the dashed curve $R = R_0$, the horizontal dashed line, and the dashed line $R = R_s$. The solid curves represents theoretical MR relations for neutron stars and strange stars.

which is plotted by dashed curve in Fig. 2.

A second constraint on the mass and radius of 4U 1728-34 results from the requirement that the inner radius R_0 of the disk must be larger than the radius of the last stable circular orbit R_{ms} around the star:

$$R_0 \geq R_{\text{ms}}. \quad (10)$$

To make our discussion more transparent, neglect for a moment the rotation of the compact star. For a non-rotating star $R_{\text{ms}} = 3R_s$, then the second condition gives:

$$R_0 \geq 3R_s = 8.86 (M/M_\odot) \text{ km}. \quad (11)$$

Therefore, the allowed range of the mass and radius for 4U1728-34 is the region in the lower left corner of the MR plane confined by the dashed curve ($R = R_0$), by the horizontal dashed line, and by the Schwartzschild radius (dashed line $R = R_s$). In the same figure, we compare with the theoretical MR relations for non-rotating neutron stars and strange stars, for the same models for the EOS considered in Fig. 1. It is clear that a strange star model is more compatible with 4U 1728-34 than a neutron star one. Including the effects of rotation ($\nu_0 = 364$ Hz) in the calculation of the theoretical MR relations and R_{ms} , does not change the previous conclusion (Li *et al.* 1999b).

4. Final remarks

The main result of the present work (*i.e.* the likely existence of strange stars) is based on the analysis of observational data for the X-ray sources SAX J1808.4-3658 and 4U 1728-34. The interpretation of these data is done using *standard* models for the accretion mechanism, which is responsible for the observed phenomena. The present uncertainties in our knowledge of the accretion mechanism, and the disk-magnetosphere interaction, do not allow us to definitely rule out the possibility of a neutron star for the two X-ray sources we discussed. For example, making *a priori* the *conservative* assumption that the compact object in SAX J1808.4-3658 is a neutron star, and using a MR relation similar to our eq. (7) Psaltis & Chakrabarty (1999) try to constrain disk-magnetosphere interaction models or to infer the presence of a quadrupole magnetic moment in the compact star.

SAX J1808.4-3658 and 4U 1728-34 are not the only LMXBs which could harbour a strange star. Recent studies have shown that the compact objects associated with the X-ray burster 4U 1820-30 (Bombaci 1997), the bursting X-ray pulsar GRO J1744-28 (Cheng *et al.* 1998b) and the X-ray pulsar Her X-1 (Dey *et al.* 1998) are likely strange star candidates. For each of these X-ray sources (strange star candidates) the conservative assumption of a neutron star as the central accretor would require some particular (possibly *ad hoc*) assumption about the nature of the plasma accretion flow and/or the structure of the stellar magnetic field. On the other hand, the possibility of a strange star gives a simple and unifying picture for all the systems mentioned above. Finally, strange stars have also been speculated to model γ -ray bursters (Haensel *et al.* 1991, Bombaci & Datta 2000) and soft γ -ray repeaters (Cheng & Dai 1998a).

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In memory of Bhaskar Datta

I dedicate this paper to my great friend and colleague Bhaskar Datta, who passed away on december 3rd 1999 in Bangalore.

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